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13. ABSTRACT (Maximum 200 words) A continued study to demonstrate the viability of growth of LED and laser diode structures on ZnSe substrates as compared with heteroepitaxial growth of II-VI structures on GaAs substrates. Other key issues that were to be addressed included p-type doping of ZnSe using nitrogen plasma sources and the ohmic contact problem for p-type ZnSe.

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Optoelectronic Applications of Wide-Band Gap II-VI Semiconductors

ARO Grant Number: DAAH04-94-G-0255

J.F. Schetzina, Principal Investigator

FINAL REPORT

A. SUMMARY OF PROGRAM RESULTS

The ARPA program funded by ARO grant DAAH04-94-G-0255, J.F. Schetzina, Principal Investigator, continued an ARPA study of homoepitaxial growth of wide band gap II-VI materials on ZnSe substrates. The goal of this 12 month program was to demonstrate the viability of growth of LED and laser diode structures on ZnSe substrates as compared with heteroepitaxial growth of II-VI structures on GaAs substrates. Other key issues that were to be addressed included p-type doping of ZnSe using nitrogen plasma sources and the ohmic contact problem for p-type ZnSe. We can report substantial success in achieving all of the above program goals. Following is a listing of the principal accomplishments of the program:

1. Commercial grade ohmic contacts for p-type ZnSe. Under the current program, NCSU has developed excellent ohmic contacts for p-type ZnSe based on HgSe/ZnTeSe epitaxial layers which minimize the band offset [1-4]. Currently, at NCSU, light emitting diodes are routinely fabricated which produce 20 mA at 3.2 V using the above homoepitaxial contacting scheme. This ohmic contacting scheme forms the basis of integrated heterostructure devices for blue/green light emission applications. NCSU was awarded U.S. patent no. 5,294,833 entitled "Integrated Heterostructure of Group II-VI Semiconductor Materials Including Epitaxial Ohmic Contact and Method of Fabricating Same", which describes a variety of LED and laser

diode structures equipped with HgSe/ZnTeSe contacts which are covered by the patent.

2. A comprehensive study of the light emission from nitrogen plasmas generated in an Oxford Applied Research rf plasma source and an ASTeX ECR source was successfully completed. The results of this study, which were reported in three scientific papers [5-7] during the course of the present program, provided that first direct experimental evidence that these sources generate an appreciable flux of nitrogen atoms. The nitrogen atoms are now believed to be the species of nitrogen that is most likely responsible for the p-type doping of ZnSe and related alloys. On the basis of these studies, we have been able to optimize the p-type doping of ZnSe and related alloys. Present doping levels of ZnSe at NCSU exceed 10^{18} cm^{-3} free holes at room temperature -- the highest p-type doping level achieved in the entire world.

3. A detailed study of the surface of ZnSe substrate wafers supplied by Eagle-Picher Industries has been completed using Auger spectroscopy. The results of this study [8] showed that the, as *polished* surface of ZnSe was heavily contaminated by both oxygen (thought to be bound to Zn) and carbon. Detailed studies via Auger spectroscopy of the effects of a variety of chemicals used for degreasing (trichloroethylene, acetone, methanol) and for chemical etching (various acids, bromine-methanol, etc.) of ZnSe were completed. Working closely with Eagle-Picher personnel, we have recently improved, in a very significant way, the surface preparation of ZnSe. As a consequence, we at NCSU are now the only MBE group in the world able to prepare high quality ZnSe films and device structures on ZnSe substrates.

4. High-brightness light-emitting diodes (LEDs) operating at peak wavelengths in the blue (486-489 nm) and in the pure green (508-514 nm) spectral regions have been successfully synthesized, processed, and tested [9,10]. The II-VI double-

heterostructure (DH) devices were grown by molecular beam epitaxy (MBE) at North Carolina State University (NCSU) using (100) ZnSe substrates produced at Eagle-Picher Laboratory by the Seeded Physical Vapor Transport (SPVTTM) process [11,12]. Substrate wafers were cut from oriented 50 mm diameter by ~25 mm thick single-crystalline ZnSe ingots. The ZnSe wafers are twin-free and contain no small-angle grain boundaries. Double-crystal x-ray diffraction rocking curve studies yield FWHM (400) = 11-16 arc sec, indicating ZnSe crystal quality comparable to that of GaAs substrates.

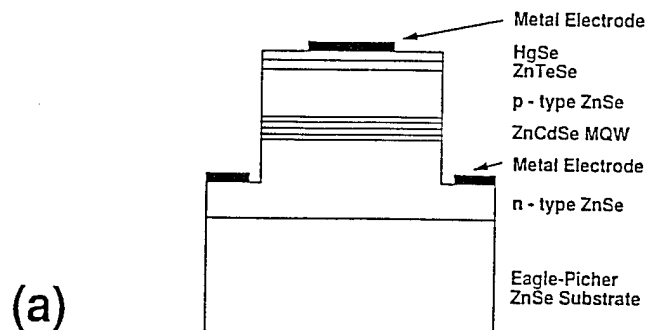
The blue and green LED device structures (Fig. 1) consist of a 2-3 μm thick layer of n-type ZnSe:Cl, a 500-1,000 \AA thick active region, and a 1.0 μm thick p-type ZnSe:N layer. For the blue LED (Fig. 1(a)), the active region consists of five 100 \AA $\text{Zn}_{0.9}\text{Cd}_{0.1}\text{Se}$ quantum wells separated by four 50 \AA ZnSe barrier layers. The active region of the green LED (Fig. 1(b)) consists of a single 1000 \AA layer of $\text{ZnTe}_{0.1}\text{Se}_{0.9}$. Thin (~100 \AA) epitaxial surface layers of HgSe/ZnTeSe were deposited by MBE to obtain better ohmic contact to the top p-type ZnSe layer. MBE growth details are discussed in previous publications [13,14].

Standard photolithographic and etching techniques [13,14] were used to fabricate 250 μm x 250 μm mesa diode structures. Gold (100 μm x 100 μm) was used as a metal contact to the top HgSe layer of each device; indium was used to contact the n-type ZnSe layer. Direct contact to the n-type ZnSe epilayer was necessitated because of the insulating nature of current ZnSe substrates. The HgSe/ZnTeSe contacting scheme produced an excellent ohmic contact, as is evidenced by the current-voltage (I-V) curve for a processed LED shown in Fig. 1(c).

The LEDs were packaged in a standard T-1 3/4 clear-epoxy lamp configuration for testing. The optical properties of the devices were measured using a Photo Research SpectraScan system which consists of a model PR-704 spectroradiometer

Blue LED Structure

Double-Heterostructure Device



Green LED Structure

Double-Heterostructure Device

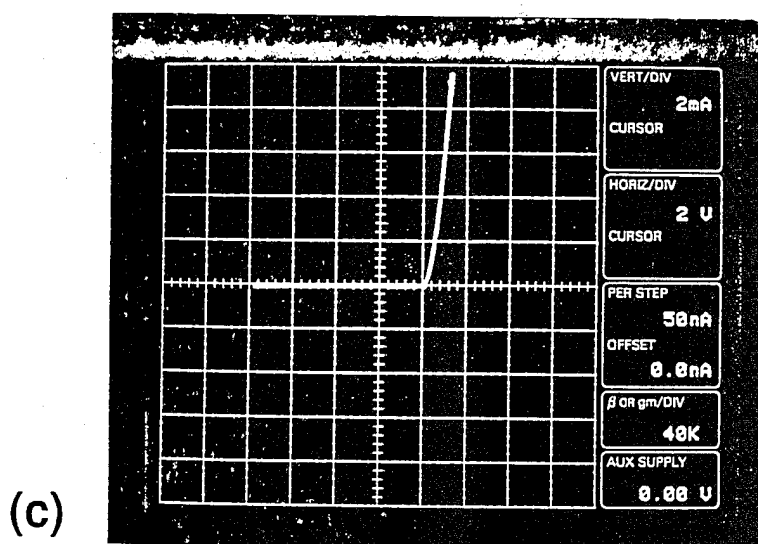
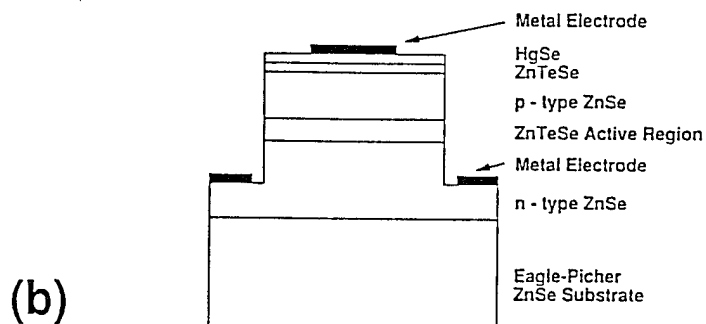


Figure 1. (a) Blue LED structure, (b) green LED structure, and (c) I-V characteristics for processed device.

to 0 °C for maximum sensitivity and efficiency, a model IS-701A/703A calibrated integrating sphere, and SpectaView computer software for measuring LED properties in both radiometric and photometric units. In radiometric units, the total LED output power or radiant flux Φ_e (in watts) is first measured. The external quantum efficiency $\eta_{q_{ext}}$ is obtained by dividing the measured radiant flux Φ_e from the device by the photon energy (in eV) of the peak emission E_{ph} , and then dividing this number by the current I (in amperes) flowing through the device [15]:

$$\eta_{q_{ext}} = \Phi_e / (I \cdot E_{ph}) \text{ (photons/electron)}. \quad (1)$$

The external power efficiency $\eta_{p_{ext}}$ is obtained by dividing the measured radiant flux from the LED by the product of the current I times the applied voltage V_{app} [15]:

$$\eta_{p_{ext}} = \Phi_e / (I \cdot V_{app}). \quad (2)$$

Finally, the luminous performance (sometimes called the luminous efficiency) $\eta_{v_{ext}}$ of the LED is obtained from the measured luminous flux Φ_v (in lumens) by dividing this quantity by the product of the current I times the applied voltage V_{app} [15]:

$$\eta_{v_{ext}} = \Phi_v / (I \cdot V_{app}) \text{ (lumens/watt)}. \quad (3)$$

Figure 2 shows plots of the light emission versus wavelength for representative blue and green LEDs based on II-VI heterostructures. The emission characteristics of an InGaN blue LED from Nichia Chemical Industries (Japan) is also shown for comparison. Fig. 2(a) shows that the light output from the ZnCdSe blue LED is sharply peaked at 489 nm with a full-width-at-half-maximum (FWHM) of 72 meV. The ZnCdSe device produces 327 μ W at 10 mA, corresponding to an external quantum efficiency $\eta_{q_{ext}} = 1.3\%$. This is approximately 30 times larger than commercial SiC LEDs and is the brightest blue LED ever made from II-VI materials.

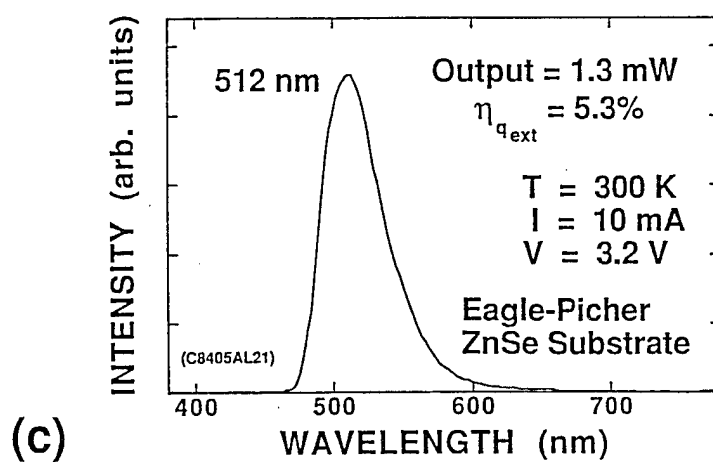
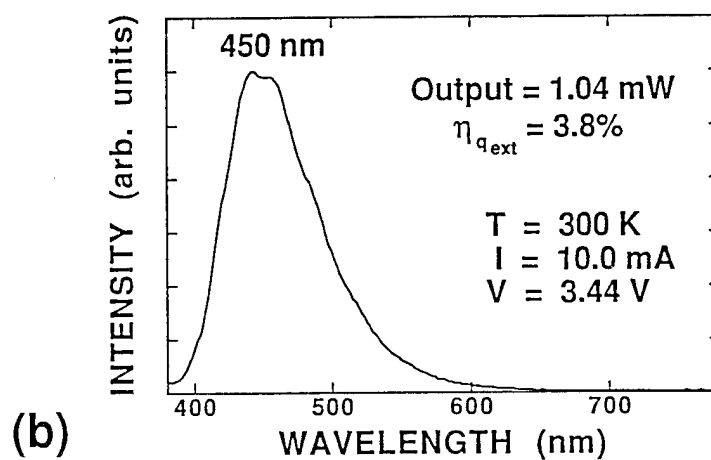
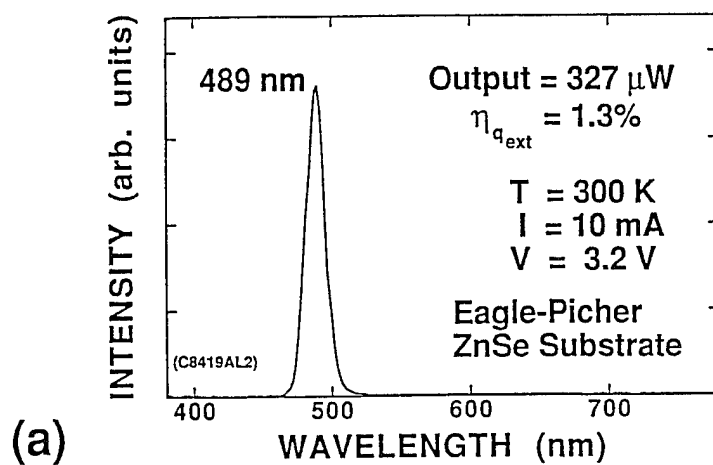


Figure 2. Light output characteristics for (a) blue ZnSe/ZnCdSe LED, (b) blue GaN/InGaN LED (Nichia Chemical), and (c) green ZnSe/ZnTeSe LED.

For comparison, Fig. 2(b) shows the emission spectrum for a Nichia Chemical Industries blue LED based on InGaN [6]. The InGaN device produces 1.04 mW at 10 mA and exhibits an external quantum efficiency of $\eta_{q_{ext}} = 3.8\%$. These are extremely impressive characteristics. Note, however, that the InGaN LED produces a very broad emission spectrum (FWHM = 510 meV) with the light output spanning from the violet to the yellow-orange spectral region. This broad spectrum, which results from the intentional introduction of Zn into the InGaN active region of the device to produce a deep-level emission peaked at ~450 nm [16], makes the output appear whitish-blue when the LED is viewed with the human eye.

Figure 2(c) shows the optical emission spectrum for a ZnTeSe green LED. The ZnTeSe device produces 1.3 mW at 10 mA, corresponding to an external quantum efficiency of $\eta_{q_{ext}} = 5.3\%$. The ZnTeSe green LEDs which we are reporting represent the brightest green LEDs ever made from any semiconductor material. They are more than fifty times brighter than commercial GaP LEDs which produce outputs peaked in the yellow-green at 555 nm. Although the presence of Te broadens the emission somewhat (FWHM = 245 meV) since Te acts as an isoelectronic hole trap, most of the light from the ZnTeSe device occurs in the blue-green to green spectral regions from 500-550 nm. The LED emission appears as a vibrant deep-green to the human eye.

Table I summarizes the results. Measured light outputs at 10 mA are given for each of the three types of devices tested. External quantum efficiencies $\eta_{q_{ext}}$, external power efficiencies $\eta_{p_{ext}}$, and luminous efficiencies $\eta_{v_{ext}}$, obtained using Eqs. (1), (2) and (3), are also listed in the table. In addition, the internal quantum efficiency $\eta_{q_{int}}$ of each of the devices was estimated using the expression [5]:

$$\eta_{q_{int}} = \eta_{q_{ext}} / \eta_{opt} \text{ (photons/electron)} \quad (4)$$

TABLE I. Summary of blue/green LED characteristics.

LED Type	Peak Wavelength (nm)	Output Power (10 mA) (mW)	η_{qext} (photons/ electron)	η_{qint} (photons/ electron)	η_{pext}	η_{vext} (lumens/ watt)
ZnCdSe	489	0.327	1.3%	7%	1.0%	1.6
InGaN [17]	450	1.04	3.8%	15%	3.0%	3.6
ZnTeSe	512	1.30	5.3%	28%	4.0%	17.0

TABLE II. Comparison of various visible light-emitting diodes.

LED Type	Peak Wavelength	Device Structure	Ext. Quantum Efficiency %	Performance lumens/watt
GaAsP	700 nm	HJ	0.2	0.15
AlGaAs	650 nm	DH-TS	16	8
AlInGaP	620 nm	DH	6	20
AlInGaP	585 nm	DH	5	20
AlInGaP	570 nm	DH	1	6
GaP	555 nm	HJ	0.1	0.6
ZnTeSe	512 nm	DH	5.3	18
ZnCdSe	489 nm	DH	1.3	1.7
SiC	470 nm	HJ	0.03	0.04
InGaN	450 nm	DH	3.8	3.6

where η_{opt} is the optical efficiency of the LED lamp which can be estimated using standard equations [15]. In these calculations, refractive indices of $n_{\text{epoxy}} = 1.50$, $n_{\text{ZnSe}} = 2.826$ at 489-512 nm, and $n_{\text{GaN}} = 2.480$ at 450 nm were used. For II-VI blue/green LEDs grown on a transparent ZnSe substrate, we obtained $\eta_{\text{opt}} \sim 0.186$. By way of comparison, if an absorbing substrate such as GaAs is used, η_{opt} is only ~ 0.037 , which significantly limits the maximum external efficiency of the device. For the InGaN LED, which was grown on sapphire, $\eta_{\text{opt}} \sim 0.251$. Thus, as calculated from Eqs. (4) and listed in table I, the ZnCdSe blue LED operates with internal quantum efficiency $\eta_{\text{qint}} \sim 7\%$ while the Nichia InGaN blue LED exhibits $\eta_{\text{qint}} \sim 15\%$ at 300K. The light output from both of these devices may be expected to increase significantly as future improvements in epitaxial growth techniques increases η_{qint} . For the ZnTeSe green LED, $\eta_{\text{qint}} \sim 28\%$. This is comparable to the internal efficiencies of commercial super-bright red LEDs and gives direct evidence that the Te isoelectronic sites in ZnTeSe provide an excellent mechanism for very efficient green light emission at room temperature. Table 2 compares characteristics of various visible LEDs.

The key issue concerning the development of II-VI blue/green light emitters which remains to be addressed is that of device degradation. All of the II-VI laser diodes and LEDs produced to date suffer from degradation of their light output [18,19]. In the case of laser diodes, the longest published cw lifetime at room temperature is only nine minutes [20]. A homoepitaxial growth approach using ZnSe substrates rather than GaAs has resulted in improved lifetimes for LEDs produced at NCSU. Fig. 3 shows 300K degradation data for two ZnTeSe LEDs operated continuously at two different dc current densities. The observed decrease in optical output power Φ obeys the equation

$$\Phi = \Phi_0 \exp [-t/\tau_d], \quad (5)$$

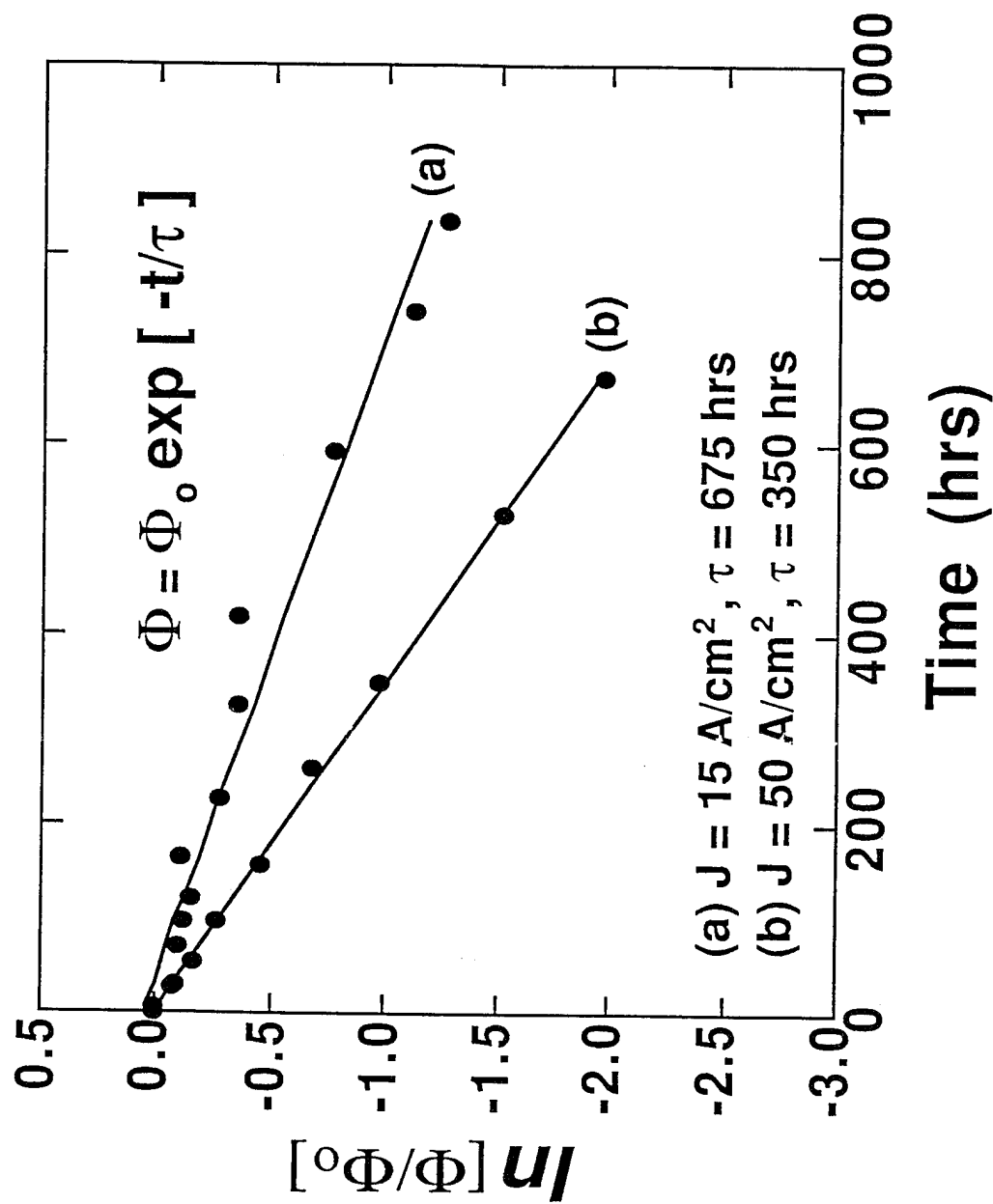


Figure 3. Natural log of Φ/Φ_0 versus time for ZnSe/ZnTeSe green LED.

where τ is the exponential lifetime of the device. For a current density $J = 15 \text{ A/cm}^2$, $\tau = 675 \text{ hrs}$. For a higher current density $J = 50 \text{ A/cm}^2$, the LED lifetime $\tau = 350 \text{ hrs}$. Thus, the degradation process accelerates as the current density flowing through the device increases. Preliminary x-ray diffraction and transmission electron microscopy experiments indicate that the dislocation density in present devices grown on ZnSe is about $10^6/\text{cm}^2$. Improvements in nucleation and growth to reduce dislocation densities are expected to increase the device lifetime substantially in the months ahead. We estimate the dislocation densities of $10^4/\text{cm}^2$ or less will be needed in order to insure long device lifetimes. We believe that this level of structural perfection is achievable.

In summary, we have demonstrated world-class blue and green LEDs based on II-VI heterostructures grown on ZnSe substrates. The blue LEDs produce $327 \mu\text{W}$ (10 mA, 3.2 V), with the light output sharply peaked at 489 nm, and exhibit an external quantum efficiency $\eta_{\text{qext}} = 1.3\%$. The green LEDs produce 1.3 mW (10 mA, 3.2 V) peaked at 512 nm, corresponding to an external quantum efficiency $\eta_{\text{qext}} = 5.3\%$. In terms of photometric units, the luminous performance η_{vext} of the devices is 1.6 lumens/watt (blue) and 17 lumens/watt (green), respectively, when operated at 10 mA. The devices also show improved lifetimes compared with similar structures grown on GaAs, although additional improvements are needed before commercialization of ZnSe-based devices becomes a reality.

STUDENT INVOLVEMENT:

Two Ph.D. students were trained under the above program of research. Jack Ren received his degree in 1994 and is currently employed by Cree Research, Inc. David Eason received his degree in 1994 and is currently employed by Eagle Picher Laboratories in Miami, OK.

PUBLICATIONS: The following presentations and papers resulted from work completed under the above program:

1. "Light Emission from Quantum Well Structures Containing ZnS, ZnSe, and Related Alloys", Z. Yu, J. Ren, Y. Lansari, B. Sneed, K.A. Bowers, C. Boney, D.B. Eason, R.P. Vaudo, K.J. Gossett, J.W. Cook Jr., and J.F. Schetzina, *Jpn. J. Appl. Phys.* **32**, 663 (1993).
2. "Improved Ohmic Contacts for p-Type ZnSe and Related p-on-n Diodes Structures", Y. Lansari, J. Ren, B. Sneed, K.A. Bowers, J.W. Cook, Jr., and J.F. Schetzina, *App. Phys. Lett.* **61**, 2554 (1992).
3. "Electrical Properties of p-Type ZnSe:N Thin Films", Z. Yang, K.A. Bowers, J. Ren, Y. Lansari, J.W. Cook, Jr., and J.F. Schetzina, *Appl. Phys. Lett.* **61**, 2671 (1992).
4. "Blue Lasers Based on II-VI Semiconductor Heterostructures", Z. Yu, J. Ren, Y. Lansari, K.J. Gossett, B. Sneed, K.A. Bowers, J.W. Cook, Jr., and J.F. Schetzina, *Mat. Res. Soc. Symp. Proc.* **281**, 543 (1993).
5. "Integrated Heterostructure Devices (IHDs): A New Approach for the Fabrication of High-Efficiency Blue/Green Light Emitters Based on II-VI Materials", Y. Lansari, Z. Yu, Z. Yang, J. Ren, C. Boney, J. W. Cook, Jr., and J.F. Schetzina, *Mat. Res. Soc. Symp. Proc.* **281**, 555 (1993).
6. "Integrated Heterostructure Devices Based on II-VI Compound Semiconductors", J. Ren, Y. Lansari, Z. Yu, J.W. Cook, Jr., and J.F. Schetzina, *J. Electronic Materials* **22**, 973 (1993).
7. "Growth of HgSe and $\text{Hg}_{1-x}\text{Cd}_x\text{Se}$ Thin Films by Molecular Beam Epitaxy", Y. Lansari, J.W. Cook, Jr., and J.F. Schetzina, *J. Electronic Materials* **22**, 809 (1993).
8. "Blue/Green Light Emitting Diodes and Laser Diodes Based on II-VI Heterostructures Grown On Pre-Deposited GaAs Buffer Layers", J. Ren, D.B. Eason, Y. Lansari, Z. Yu, K.A. Bowers, C. Boney, B. Sneed, J.W. Cook, Jr., and J.F. Schetzina, *J. Vac. Sci. Technol. B* **11**, 955 (1993).
9. "Ultraviolet Quantum Well Structures Based on $\text{ZnS}/\text{ZnS}_{1-x}\text{Se}_x$ and $\text{ZnSn}_{1-x}\text{Cd}_x\text{S}$ Multilayers Grown by MBE", R.P. Vaudo, D.B. Eason, K.A. Bowers, K.J. Gossett, J.W. Cook, Jr., and J.F. Schetzina, *J. Vac. Sci. Technol. B* **11**, 875 (1993).
10. "Photoluminescence of HgTe/CdTe Superlattices Under High Hydrostatic Pressures", H.M. Cheong, J.H. Burnett, W. Paul, and P.M. Young, and J.F. Schetzina, *Phys. Rev. B* **48** 4460 (1993).
11. "Electrical Properties of p-type ZnSe:N and ZnSSe:N Thin Films", Z. Yu, K.A. Bowers, J. Li, J. Ren, J.W. Cook, Jr., and J.F. Schetzina, *Proceedings of the 1993 Electronic Materials Conference, Santa Barbara, CA* (1993).
12. "Quaternary II-VI Alloys for Blue/Green Light Emitter Applications", K.A. Bowers, Z. Yu, C. Boney, J. Ren, J.W. Cook, Jr., N.A. El-Masry, and J.F. Schetzina, *Proceedings of the 1993 Electronic Materials Conference, Santa Barbara, CA* (1993).
13. "Blue/Green Lasers Based on II-VI Semiconductor Heterostructures", J.F. Schetzina, *Proceedings of LEOS Summer Topical Conference on Visible Lasers, Santa Barbara, CA* (1993).

14. "Blue/green Laser Diodes and Light Emitting Diodes", Z. Yu, J. Ren, J.W. Cook, Jr. and J.F. Schetzina, *Physica* **B191**, 119 (1993).
15. "Atomic-Nitrogen Production in a Radio-Frequency Plasma Source", R.P. Vaudo, X. Yu, J.W. Cook, Jr., and J.F. Schetzina, *Optics Letters* **18**, 1843 (1993).
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22. "Optical Properties of Nitrogen-Doped ZnSe and ZnSSe Thin Films", K.J. Gossett, Z. Yu, K.A. Bowers, J.W. Cook, Jr., and J.F. Schetzina, *J. Elec. Mat.* **23**, 251 (1994).
23. "Integrated Heterostructure Devices Composed of II-VI Materials with Hg-Based Contact Layers", J. Ren, D.B. Eason, L.E. Churchill, Z. Yu, C. Boney, J.W. Cook, Jr., J.F. Schetzina, N.A. El-Masry, *J. Cryst. Growth* **138**, 455 (1994).
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25. "Femtosecond Wave Mixing Experiments in ZnCdSe/ZnSe Quantum Wells", D.S. Kim, A.J. Fischer, J. Hays, W. Shan, J.J. Song, D.B. Eason, J. Ren, and J.F. Schetzina, *Appl. Phys. Lett.* **65**, 1534 (1994).
26. "Current-Voltage Characteristics of Electric Contacts on p-Type ZnSe", Z. Yang and J.F. Schetzina, *J. Elec. Mat.* **23**, 1071 (1994).
27. "Femtosecond Coherent Spectroscopy of Bulk ZnSe and ZnCdSe/ZnSe Quantum Wells", A.J. Fischer, D.S. Kim, J. Hays, W. Shan, J.J. Song, D.B. Eason, J. Ren, J.F. Schetzina, H. Luo, J.K. Furdyna, Z.Q. Zhu, T. Yao, J.F. Klem, and W. Schafer, *Phys. Rev. Lett.* **73**, 2368 (1994).

28. "High-Brightness Blue and Green Light-Emitting Diodes", D.B. Eason, Z. Yu, W.C. Hughes, W.H. Roland, C. Boney, J.W. Cook, Jr., J.F. Schetzina, G. Cantwell, and W.C. Harsch, *Appl. Phys. Lett.* **66**, 115, 1995.
29. "Blue and Green Light-Emitting Diode Structures Grown by MBE on ZnSe Substrates", D.B. Eason, J. Ren, Z. Yu, W.C. Hughes, J.W. Cook, Jr., J.F. Schetzina, N.A. El-Masry, G. Cantwell and W.C. Harsch, to be published in *J. Cryst. Growth*, 1995.
30. "MBE Growth of II-VI Light-Emitting Devices on GaAs Substrates Using Valved Sources for S and Se", M.A.L. Johnson, Z. Yu, J.W. Cook, Jr., and J.F. Schetzina, to be published in *J. Vac. Sci. Technol.* **B 13**, 746 (1995).
31. "High-Brightness II-VI Light Emitting Diodes Grown by MBE on ZnSe Substrates" Z. Yu, D.B. Eason, J. Ren, W.C. Hughes, W.H. Rowland, Jr., N.A. El-Masry, J.W. Cook, Jr., J.F. Schetzina, G. Cantwell and W.C. Harsch, *J. Vac. Sci. Technol.* **B 13**, 711 (1995).
32. "High-Brightness Light-Emitting Diodes Grown by MBE on ZnSe Substrates", D.B. Eason, Z. Yu, W.C. Hughes, W.H. Roland, C. Boney, J.W. Cook, Jr., J.F. Schetzina, G. Cantwell, and W.C. Harsch, to be published in *IEEE Spectrum*, 1995.
33. "MBE Growth and Properties of GaN on GaN/SiC Substrates", W. C. Hughes, J.W. Cook, Jr., J. F. Schetzina, J. Ren and J. A. Edmond, to be published in *JVST*, 1995.
34. "High-Brightness Light-Emitting Diodes Grown by MBE on ZnSe Substrates", D.B. Eason, Z. Yu, W.C. Hughes, C. Boney, J.W. Cook, Jr., J.F. Schetzina, Gene Cantwell, and William C. Harsch, to be published in *JVST*, 1995.

INVITED PRESENTATIONS:

1. "Blue/Green Laser Diodes and LEDs", SDI Technology Applications Review, Pasadena, CA (1993).
2. "Blue Semiconductor Lasers Based on Wide-Band-Gap II-VI Materials", ARPA Optics Symposia, Hilton Head Island, SC (1993).
3. "The Blue Semiconductor Laser", with R.L. Gunshor, American Physical Society, National Press Club, Washington, DC (1993).
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